Heliyon 7 (2021) e08221

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Harnessing energy from the waste produced in Bangladesh: evaluating potential technologies

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ARTICLE INFO

Keywords:
Waste to energy
Solid waste
Waste generation technologies
Energy conversion
Bangladesh

ABSTRACT

With the increasing trend of the urban population in Bangladesh, waste generation is also increasing. With 70% organic solid waste, the urban areas generate 23,688 tonnes of waste per day. This rapid enhancement in waste production has an adverse effect onlandfill resources and the day-to-day lifestyle. In this regard adopting waste to energy techniques can be considered good idea to overcome the current waste management problem. This WtE conversion technique solves the landfill resources problem and produces electricity and heat to be supplied. This study aims to investigate the current status of MSW management in Bangladesh and identify the major problems. Here, five fundamental methods such as pyrolysis, incineration, anaerobic digestion (AD), gasification, hydrothermal carbonization (HTC) are reviewed critically and discussed the feasibilities in Bangladesh to generate power. The analysis is done considering different types of parameters like moisture content, calorific value, and residence time. These analyses pertaining to MSW management may be fruitful for encouraging researchers and authorities to improve further.

1. Introduction

Due to the population growth and diverse consumption habits and patterns of developed communities, solid wastes have put significant pressure on the environment. Over the last few years, the demand for environmentally sound municipal solid waste management (MSW) has increased extensively [1]. If the rapid increase in urban-waste footprint is not handled correctly, it will surely have a negative impact on sustainable livelihood, the local environment (air, water, land), and human health [2]. In this scenario, waste to energy can represent a fundamental strategy in the waste treatment area. The technology is linked to waste disposal and purification and the maximum use of energy in the flue gas. Therefore, its importance is going to be increased more in the future [3].

Recently, Bangladesh has faced a rapid growth of industrialization and change in the financial sector and trade [4]. The urban population of Bangladesh was only 23.6% of the total population in 2000, and by 2019, it jumped to 37.4% [5]. This excessive migration has created slums and unplanned urbanization, resulting in a plethora of unmanaged solid waste (SW) in all major cities like Dhaka, Chittagong, Sylhet, Khulna, Rajshahi, etc Barisal. In addition, during the period of 1990s, a lot of industrial plants were built up in different districts, such as Chittagong, Dhaka, Gazipur, and Narayanganj [4].

In Bangladesh, plastics, metals, and glass have been recycled partially by informal sectors. Different NGOs took the responsibility of composting organic waste and the recycling sector. Nevertheless, generating a large portion of organic waste is still a serious concern [6]. This portion consists of almost half of waste generation and requires costly disposal and removal [6, 7]. Recently, the government of Bangladesh and some private NGOs have taken some initiatives to utilize these wastes and convert them to energy.

The population of Bangladesh is increasing day by day. Therefore, the amount of waste is also growing. From 2008 to 2018, the urbanization rate of Bangladesh increased from 28.97% to 36.63% [22]. To utilize these wastes as energy, pyrolysis and incineration are being practiced generally in Bangladesh. On the contrary, anaerobic digestion (AD) and gasification process are not being applied that much due to machine cost, installation cost, land, and operation cost. In addition, HTC (hydrothermal carbonization) is a new technology that has not achieved that much familiarity yet in Bangladesh. In this regard, an intensive study is necessary to get familiar with the unpracticed processes and find the most good ways to practice them from the perspective of Bangladesh.

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https://doi.org/10.1016/j.heliyon.2021.e08221
Received 18 May 2021; Received in revised form 27 July 2021; Accepted 15 October 2021

Pyrolysis and incineration are the standard technology in the perspective of Bangladesh.

Moreover, AD and gasification processes are expanding rapidly. As modern technology, HTC is economical and environmentally friendly. Soon, an extensive remarkable contribution can be expected from this technology in Bangladesh. All process has been discussed in this review, and an attempt has been made to find out which process is suitable for Bangladesh, but no other review article has discussed in this way. This in-depth review would be helpful for researchers to find the proper waste-to-energy (WtE) technology and the renewable source of energy from solid waste generated in Bangladesh.

1.1. The energy potential of MSW

Low calorific value (LCV) represents the energy potential of waste that would be utilized efficiently during thermal treatment later, thus affecting a waste to energy plant's economy [8]. The most important thing to consider in the strategy to get energy from MSW is the energetic content of each MSW fraction. LCV would be very useful in setting balances for multiple scenarios to avoid issues with components being landfilled. The recommended high heating value (dry basis) and low heating value (dry basis) are 19.48 MJ/kg and 17.97 MJ/kg, respectively [9]. Typically, about 6–7 MJ/kg MSW can be found where low-medium income economic characteristics exist.

In contrast, LCV can reach about 13 MJ/kg while economic development is enhanced with the light packaging of MSW. If the comparison is made of selective collections (SC) of about 35% efficiency with another sample of SC having 65% efficiency, the stream of RMSW (residual waste) has been found almost half of the initial value [10]. Therefore, it is indispensable to perform a suitable analysis of the available selections for MSW treatment processes. However, the author [11] calculated LCV for Dhaka and Chittagong city of Bangladesh. To calculate the LCV value, the author considered typical heat values of MSW components, e.g., food waste 957.13 $\times$ 10^{-6} MJ/kg, paper 3445.68 $\times$ 10^{-6} MJ/kg, plastics 6699.94 $\times$ 10^{-6} MJ/kg, textiles 3589.25 $\times$ 10^{-6} MJ/kg, glass and ceramic 28.71 $\times$ 10^{-6} MJ/kg, metals 143.57 $\times$ 10^{-6} MJ/kg, grass and straw 1339.99 $\times$ 10^{-6} MJ/kg, Others 1435.7 $\times$ 10^{-6} MJ/kg. The result showed that LCV of MSW for Chittagong city was 8.44 MJ/kg and 6.32 MJ/kg for Dhaka city during ultimate analysis. Furthermore, according to the composition of SW, the LCV of MSW in Dhaka and Chittagong was 0.71 MJ/kg and 1.06 MJ/kg, respectively. However, the ultimate analysis has pointed to higher LCV values in both cities.

The LCV value of different types of waste is expressed in Figure 1. As shown in Figure 1, the LCV value of rubber, composite and plastic waste is comparatively higher than other wastes. Among them, the LCV of plastic is higher (32000 $\times$ 10^{-6} MJ/kg), while the paper is at least about 1200 $\times$ 10^{-6} MJ/kg. The energy potential of waste is determined by LCV, which can be later effectively utilized in the thermal treatment and contributes significantly in the economy of waste to energy plants [8]. Since the LCV value of plastic is 32000 $\times$ 10^{-6} MJ/kg and it can be said that by plastic waste, the economic development is enhanced with light packaging of MSW in Bangladesh. Again, the LCV of wood, textile, and hazardous textiles (contains heavy metal such as lead or cadmium) components are comparatively higher than food and paper waste. Therefore, their role in thermal treatment is also essential.

To solve the issues regarding waste treatment and convert it to energy, it is essential to recognize the composition, characteristics, state, etc. of the waste. The selection of proper techniques for different regions and waste types is also essential. The optimal choice should include two requirements: economic and environmental. Different conditions must be fulfilled to select waste processing technologies. First, the technology for each application needs to be customized in most cases [12]. From the technological point of view, the best available technologies – BAT – are usually chosen [12, 13]. However, for only a few (sometimes none of them) can be applied for different purposes. The creativity and the potential of (to be selected) technology providers will play a significant role [12]. There are no general instructions or guidelines for proceeding, but certain general and particular criteria must be considered [12].

Waste collection, treatment, management, and disposal are significant concerns for waste to energy process. Pyrolysis is the most effective process in Bangladesh for renewable sources; but, not an approved authorization for MSW disposal since the most critical factor is the heating rate, and the heating rate varies from 40 °C min^{-1} to 670 °C min^{-1} [14]. Without oxygen in this thermal degradation method, different recyclable products, for example, char, oil, and combustible gases, can be produced. In this method, a combination of carbon dioxide and methane are major components and traces of hydrogen sulfide; hydrogen, ammonia etc. are also produced. Besides, under high temperatures, the gasification process helps to transform low-grade solid biomass into gasses known as syngas. Biomass-generated syngas mainly includes CO, H_2, CO_2, CH_4, N_2, and impurities such as tar, H_2O, NH_3, and H_2S [15]. So, it is clear that a substantial amount of tar can be produced during the pyrolysis step in the gasification process. Due to impurities in the pyrolysis products, the product improvement facility should be provided with a single pyrolysis process. This is why cumulative pyrolysis and gasification and/or combustion technologies have been used for commercial pyrolysis plants. To remove tar and reduce emission clean syngas must be needed by using an emission control device [14]. Thus, pyrolysis is a better solution to reduce gas emission and has an opportunity to wash syngas before the combustion process [14].

Nevertheless, the combustion of waste for recovering energy, i.e., incineration, has higher efficiency than pyrolysis. Incineration plays a significant role worldwide and can also minimize fossil fuel dependency [16]. Furthermore, HTC may be a very effective technology for producing

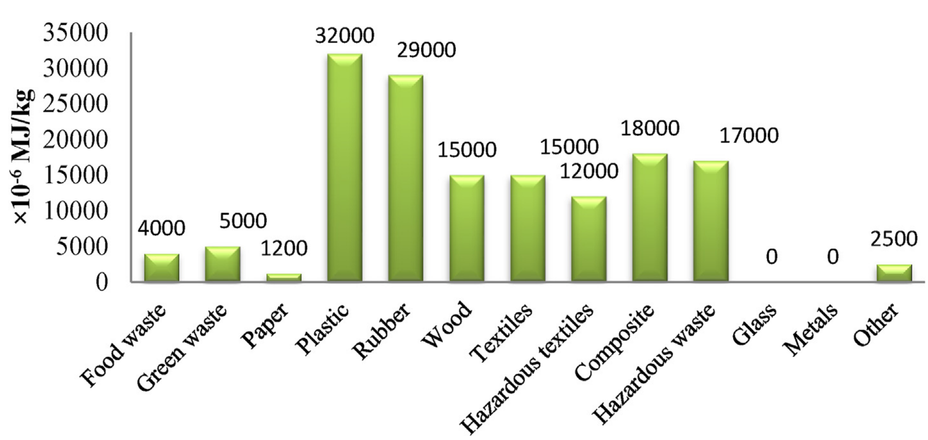

Figure 1. LCV of each MSW fraction [17, 18].

biochar and energy. Though this method is yet not well established for the WtE process, this method is environmentally friendly, may occupy a better place in the future.

Generally, the waste-to-energy (WtE) processes are less efficient than conventional fossil fuel power plants because of the specific equipment requirement, like output pressure reduction to avoid corrosion risk. In this paper, we have discussed the current waste generation of Bangladesh along with already established WtE techniques and the potentiality of other techniques. All methods are evaluated considering different parameters, geographical position, and economy. Finally, based on all the discussions, some recommendations are provided. This is the very first review that discusses some potential methodologies which can be implemented in Bangladesh. Further, the authors have also discussed the Circular bio-economy (CBE) in Bangladesh, which is not evaluated in other kinds of literature.

2. MSW management and present scenarios in Bangladesh

The MSW production in Asia is expected to be 1.8 million tonnes per day in 2025 from the current 1 million tonnes/day rate for waste production [19]. The increasing amount of energy is a major challenge for some developing countries like Bangladesh and India. In Bangladesh, there are more than 160 million inhabitants, 29.4% of whom live in urban areas [20]. The amount of solid waste production in urban areas of Bangladesh is around 25,000 per day, which translates into 0.465 kg/capita/day [21]. Household solid waste (HSW) contributes to around 90 % of total MSW waste and about 80%–92% is organic solid waste (OSW) [22]. Due to a large amount of waste, human's everyday life, environment, and health are being threatened. To solve all these problems, proper waste management is essential, through which it is possible to recover energy. There are many other ways to recover energy from solid waste. Many MSW generation is already responsible for major environmental issues in Bangladesh because of speedy urbanization and ongoing economic development [11]. In different cities in Bangladesh, the waste generation rate ranges between 0.25 to 0.70 kg/capita/day, where maximum waste generation occurs in Chittagong city (0.56 kg/capita/day) and Dhaka city (0.70 kg/capita/day) (Table 2). Almost 78% is generated from the residential sector, 20% from industry, and the remainder is from other sectors [19].

In Bangladesh, the MSW management system is mainly governed by the Japan International Cooperation Agency (JICA), and other initiatives are underway with WCG (Waste Concern Group), UNICEF (United Nations Children's Fund), UNDP (United Nations Development Programme), and NGOs (Non-Governmental Organizations) like BRAC (Bangladesh Rural Advancement Committee) [23]. These organizations usually discuss and help in the development, feasibility analysis, financial availability, and international collaboration of a developing country's internal programs or projects. According to them, the efficiency of waste collection data in various urban areas ranges from 37% to 77%, and the average is 55% [24]. As a result, the waste collection rate is not adequate, and cannot collect a significant amount of waste properly, and the main problem is the lack of collection data. In recent years, it is seen that uncollected organic garbage causing air pollution in the local environment, blocking the drainage system, and water stagnation after each rainfall. However, the City Corporation and Municipal authorities are trying to take action, but that is not sufficient because only trucks are available to collect the garbage from the bins and take those to landfills, which are open places.

Moreover, as the population of Dhaka, Chittagong and Sylhet are high, more waste is generated here, which accounts for around 0.6 kg/capita/day, 0.61 kg/capita/day, and 0.43 kg/capita/day respectively [25]. According to BIGD (Brac Institute of Governance and Development) [26], Dhaka generates 3,200 tonnes/day of solid waste, and its per capita waste generation is 0.438 kg/day. The Dhaka city corporation is working with NGOs and CBO (Community-Based Organization) and 300 vans, and 3,000 waste cleaners of NGOs & CBO for primary to secondary waste collection [27].

3. Waste production and treatment in Bangladesh

Improvement of day-to-day lifestyle and high consumption patterns lead to an unintentional and negative impact on urban waste generation far beyond the urban government and organizations' capacity to handle [28]. From 2008 to 2018, the urbanization rate of Bangladesh increased from 28.97% to 36.63% [29]. It is reported that the present population of Bangladesh is 164,802,127, and the population growth rate is 1.01% per year [30]. This rapid population growth leads to an increasing order of waste produced every year. In 2012, the waste production rate was 0.41 kg/cap/day and during this year, almost 22.4 million tons of waste were produced [31]. It is estimated that the number would increase to about 47,064 tons a day, and the generation rate would be 0.602 kg/capita/day due to a growing population and the production of per capita waste. Based on the waste generation scenario, the average waste management efficiency indicates the waste collection efficiency in urban areas is about 55% (average) and generally varies from 37% to 77% [32, 33]. From Table 1, a summary can be obtained about the effect of the growing population on waste produced every year. It can be seen that due to the rapid growth of population, the urban areas of Bangladesh generate approximately 16,015 tonnes of waste per day, which adds up to over 5.84 million tonnes annually [34]. Hence, the total production per day is also increased at an alarming rate of about 6,506.5 tons.

The extrapolated data in 2025 shows a warning that if no proper management is taken, the waste production rate will increase at a high amount with the growing population. It is also reported that six major cities of Bangladesh generate approximately 7,690 tons of solid waste every day. The composition of the entire waste stream consists of 74.4% organic matter, 9.1% paper, 0.8% leather and rubber, 3.5% plastic, 1.9% textile and wood, 1.5% metal, 0.8% glass, and 8% other wastes [35]. The major factors contributing to waste generation are population, fruit season, lifestyle, climate, economic conditions, and waste management techniques [6]. Recently, the government of Bangladesh has undertaken a constructive step called the “3Rs” strategy. The main objective of this process is to reduce, reuse and recycle the waste [36]. This initiative assists the existing authorities to handle and separate the biodegradable and non-degradable waste.

Moreover, people are encouraged to keep the recyclable, non-recyclable, degradable, and non-degradable waste in a separate bag or container. These separated containers are further collected and used to throw them into a particular municipal waste point. After approval from the authorities, these wastes are collected by the relevant recycler. Besides, some NGOs and volunteers are also participating in some public awareness and educational programs.

According to JICA [23], Various sources such as domestic, commercial, industrial, street sweeping, and health care facilities are responsible for the generation of wastes. During the wet season, the rate of waste generation is comparatively higher than the dry season. In the wet season, the waste generation per capita per day is estimated at 0.5 kg, whereas in the dry season, it amounts to 0.34 kg per capita per day [37]. Table 2 demonstrates an estimated growth rate of MSW and their physical components (based on wet weight %) in the major cities of Bangladesh. All six cities generate a total of 7,690-8,000 tonnes per day of MSW, and the contribution of DCC (Dhaka City Corporation) is around

Table 1. Urban solid waste production in Bangladesh, adapted from [6].

Year	Total Urban Population	Urban population (% total)	Waste production rate (kg/capita/day)	Total waste production (tonne/day)
1991	20872204	20.15	0.49	9873.5
2001	28808477	23.39	0.5	11,695
2004	32765152	25.08	0.5	16,382
2025 (forecast)	78440000	40.0	0.6	47,064

Table 2. The physical component of MSW and Waste generation rate (WGR) in major cities in Bangladesh [6, 39, 40, 41, 42].

Composition	Wet weight %						
	Dhaka city corporation (DCC)	Chittagong city corporation (CCC)	Khulna city corporation (KCC)	Rajshahi city corporation (RCC)	Barisal city corporation (BCC)	Sylhet city corporation (SCC)	Average of wt %
Foods, vegetables	68.3	73.6	78.9	71.1	81.1	73.8	74.5
Paper and its products	10.7	9.9	9.5	8.9	7.2	8.4	9.1
Polythene and plastics	4.3	2.8	3.1	4.0	3.5	3.4	3.5
Textile and wood	2.2	2.1	1.3	1.9	1.9	2.1	1.9
Rubber and leather	1.4	1.0	0.5	1.1	0.1	0.6	0.8
Metal and tins	2.0	2.2	1.1	1.1	1.2	1.1	1.4
Glass and ceramic	0.7	1.0	0.5	1.1	0.5	0.7	0.8
Brick, stone and concrete	1.8	1.1	0.1	2.9	0.1	1.8	1.3
Others (rope, bone, etc.)	1.9	1.2	1.2	1.3	1.3	2.8	1.6
WGR (waste generation rate)							
Population, in million	7.23	2.66	0.67	0.46	0.35	0.51	-
Waste generation (kg per capita per day)	0.70	0.56	0.48	0.27	0.44	0.25	0.3

70% [38]. The waste generation per capita per day is also highest in Dhaka City corporation because of its massive population. Table 2 also represents that foods and vegetables contribute approximately more than two-thirds of total waste generation. This is because of the over-reliance of people on them and the unawareness during consumption, preservation, and processing. However, glass and ceramic contribute lesser than all other composition in total waste generation in every city (Table 2).

3.1. Physical and chemical components of solid waste

The contribution of MSW of Dhaka city is higher than in other cities (Table 2), and chemical components (Table 3) are higher in Dhaka city compared to other cities. However, VFW is higher for CCC (Chittagong City Corporation) because of a lower socioeconomic group [43, 44, 45]. It is found that the higher volatile soil usually contains a higher calorific value, but soil fertility (the ability of soil to sustain agricultural plant growth) may improve with a higher content of nutrient elements [22]. However, because of alteration in sampling and testing methods, the chemical components in the MSW which researchers investigated were not consistent. For instance, Halder et al. [46] revealed 50.2% C, 1.9% N_2, 0.1% S, 7.0% H_2, 40.2% O_2, and 0.2% others in Rajshahi MSW, whereas Rouf [47] reported that 51.5% C, 7.9% H_2, 40.6% O_2, 2.4% N and 0.2% Sulphur were in Rajshahi. Also, a high C/N ratio is highly potential for organo-mineral fertilizer production in MSW [48].

To define an alternative energy recovery period, the physical characteristics and, waste streams of an urban area are essential, such as a waste weight fraction, a dry weight fraction, and a moisture content. Conversely, this decision is also influenced by chemical properties, organic molecular composition, inorganic CO_2, H_2, O_2, N_2, sulphur, and ash.

Table 3 represents the chemical components of the major cities of Bangladesh. The analysis of Table 3 illustrates that waste from Dhaka city, Khulna, and Sylhet city has higher moisture content than other cities, which is about 68–70%. If the moisture content in waste is high, biodegradation increases, and landfill gas generation will expand. Consequently, methane gas increases and reduces landfilling stabilization time, which plays a significant role in energy recovery. Again, from the below table, it can be seen that the amount of pH is higher in Dhaka city as MC (moisture content) is around 8.70%, whereas the amount of MC and pH is less in Barisal city. The high pH level in DCC is the high concentration of short-chain organic acid (lactic and acetic acid) in the waste. However, the pH level indicates the maturity of the compost of organic waste. As such, Barisal city has a pH of 7.70, which is lower than in other cities. Due to the low pH conditions, the decomposition rate can be slow for organic waste in Barisal. Besides, K and P help to increase the organic manure of solid waste.

Moreover, the C/N ratio of the waste of Chittagong is high enough to produce organo-mineral fertilizer, and the volatile solid percentage of DCC is excellent for producing high-quality biogas. Here, CH_4: CO_2 (methane and carbon dioxide index) is a biogas quantity indicator. A higher index means a higher quantity of biogas and, high volatile is an operational parameter. During any biological process, volatility should be satisfied to achieve high-quality biogas output.

Sensitivity analysis is how the dominance of moisture content on the overall efficiency of MSW can be evaluated quickly. Islam et al. [11] investigated the analysis with the varying moisture content of the MSW

Table 3. Chemical characteristics of MSW in the city of Bangladesh [19, 49].

Parameters	Dhaka city corporation	Rajshahi city corporation	Khulna city corporation	Barisal city corporation	Sylhet city corporation	Chittagong city corporation
pH	8.69	7.72	7.76	7.70	7.71	8.23
MC (%FM)	70	56	68	57	69	62
C/N	10.17	12.15	16.08	12.44	11.96	17.22
Ash residue (%DM)	29	52	44	57	35	46
N_{total} (%DM)	0.89	0.56	1.62	1.23	0.90	0.17
Volatile solid (dead animal matters, plants & synthetic organic compound, % DM)	71	48	56	43	65	54
K_{total}(%DM)	0.62	0.38	1.37	1.18	0.42	0.57
P_{total}(%DM)	0.31	0.31	0.41	0.40	0.32	0.23

**Note: DM = Dry matter; FM = Fresh matter.

in the ±0–30% range. This result revealed that as moisture content increased or decreased, the amount of energy, electricity generation, and GHGs emissions changed in retrospect at a magnitude of 2%, 4.3%, and 9.5%. The author concluded that MSW preheating would increase energy potentials in Dhaka City and Chittagong of Bangladesh, reducing moisture content and reducing GHG emissions [11].

4. Waste to energy conversion technologies

The management of municipal solid waste has become a crying need in some developing countries like Bangladesh., especially in urban areas [50]. On the contrary, developed countries were trying to handle the wastes safely and disposed of economically and technologically. They are also trying to practice contemporary waste treatment technologies like Anaerobic Digestion (AD), incineration, pyrolysis, gasification, and recycling for utilizing the waste into harnessing energy [51]. However, Bangladesh is barely familiar with some standard techniques without updated knowledge, and most of the modern technologies are not being practiced here. Although the government of Bangladesh and NGOs are thinking about the technologies, technologies are becoming challenging to adapt to the population growth of Bangladesh. With the increase in population, waste management is being disrupted, and the energy crisis is taking a terrible turn. Because of the significant contribution of fossil fuel in the energy mix, the energy source is not sustainable [52, 53]. In this context, itmay be a feasible substitute for renewable and alternative power generation with MSW management in Bangladesh. To achieve zero waste society and adopt the circular economy principle, implementing the WtE strategy will support Bangladesh's elaborate at the national level [54]. Hence, the proper and updated bits of knowledge are become a dire need to ensure a sound solid waste management. The below section discusses about some techniques regarding energy generations from wastes that can be applied in Bangladesh.

4.1. Incineration

"Incineration" is a waste processing technology that includes energy recovery from waste combustion. The materials that can be incinerated are plastic, rubber, cloth, and diesel engine scavenge scraping, food waste, hospital waste, and female hygienic binds. In this technique, the waste material is burned between the temperature of 900 °C to 950 °C with the help of fuel gas (mainly a mixture of CO_2, CH_4, and H_2) [55]. This high-temperature range can be applied for producing energy, and this energy can be used as heat energy, and further, it converts into electrical energy [55, 56]. The main purpose of this process is to decrease waste weight and volume and turn it into energy with the help of oxygen and air. About 90% of MSW volume can be reduced by incineration [16]. During this process, harmful gaseous pollutants like SOx, CO_X, NO_X, and Polyaromatic hydrocarbons can be generated. Therefore, the Art flue system needs a proper cleaning before the ultimate discharge in the environment [57]. Air pollution control systems can reduce the emission of the regulated emission limit. For example, for emissions like NOx (400 mg/Nm^3), dioxins and furans (0.1 ng/m^3), sulfur dioxide (200 mg/Nm^3), carbon monoxide (100 mg/Nm^3), HCl (60 mg/Nm^3), HF (4 mg/Nm^3), total organics (20 mg/Nm^3), mercury (0.05 mg/Nm^3), and metals (Cd, Ti, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, and V – 0.05 to 0.5 mg/Nm^3) [58]. The ash is formed at the bottom, which is biologically clean, and is often utilized for road buildings and construction industries [59]. The produced fly ash and flue gas are hazardous and treated under an air pollution control system. However, modern incineration plants consist of an air pollution control system that restricts the pollution of air.

Incineration is an essential process for producing heat and steam from municipal solid waste (MSW). This generated heat and power can be provided in urban areas. In Brazil, an implemented power plant showed that it could produce three times more energy than produced for the equal waste mass by landfill biogas [60]. It is reported that the energy efficiency of heat generation through this technique is 80% [57]. Moreover, the efficiency of generating steam and electricity ranges from 20-30% [57]. When analyzing the revenues through power generation, it indicates that the value of incineration seems to be very high (€32.64/ton) compared with landfills or other final disposals [61].

Though there are two incineration plants installed at Amin Bazar and Matuail at Dhaka city, which were established in partnership with an Italian company called Management Environment Finance SRL Ltd, the plants remain obsoleted because they are not being able to operate properly [62]. China recently proposed constructing a plant in Dhaka city, but it is still at the primary construction level [63].

The characteristics of the MSW and possible renewable energy potential (REP) of some major cities in Bangladesh are shortly described below:

- Dhaka city: Considering the moisture content (MC) (68.3%) of MSW, Dhaka city can be supplied 100 MW electricity, and total Renewable energy potential (REP) is 1399.6–712 GWh by 2030, 1.18–1.44 MT CO_2 can eliminate associated with greenhouse gases [54, 64].
- Chittagong: The total REP is 726.7–600.3 GWh, associated with GHG reduction of 0.64–0.76 MT CO_2 by 2020, in Chittagong [22, 65].
- Khulna city: About 549 tonnes of MSW can generate 22,932.78 kWh/day electricity from gas produced by MSW [22].
- Rajshahi city: At Rajshahi city, the total REP was found to be 544 MWh per day and 119.8 MWh per day from bagasse and MSW, respectively, for 56 days [66], also it showed a better calorific value of about 15.51 MJ/kg with MC (50–60%) in MSW as shown in Table 4.
- Pabna: The possible REP was found in Pabna about 519.14 kWh per day from a higher amount of organic materials (OM) contained MSW [67].

Waste energy recovery (WER) is converted through various processes (pyrolysis, gasification, AD, etc.) of non-recyclable waste materials into useable heating, electricity, and fuel. From Table 4, it can be seen that energy recovery value in Dhaka and Chittagong is 8000 kWh/day and 8890 kWh/day, respectively. WER is highest in Chittagong city, which is about 80% higher than Pabna. It is also worth noting that the number of organic materials in Dhaka and Chittagong city is more than in Pabna and Rajshahi. So, organic materials 75.75% in Chittagong city, for which WER is 8,890 kWh/day. Thus, it can be said that the amount of methane emission from other places in Chittagong and Dhaka city is comparatively less because energy recovery decreases the demand of fossil fuel-based energy source and also reduce methane emissions generated by landfills.

Nonetheless, renewable energy potential indicates the amount of energy that can be used in a renewable resource from waste. The higher the renewable energy potential, the lower the demand and price for natural gas and coal, and the lower the demand for fossil fuel. That is,

Table 4. Moisture content, Calorific value, and REP from MSW by Incineration [66, 67, 68].

Name of the cities	OM (%)	MC (%)	C (wt.%)	CV (MJ per kg)	REP	ER (kWh/day) (ER = E_{np} = TE_p – S_A – U_H)
Dhaka	68.3	50–60	40.0	5.67–6.94	1399.6 GWh	8000
Pabna	69	60	45–75	4–6.65	519.14 KWh	519.14
Rajshahi	70	50–60	50.23	15.51	544 MWh	4482
Chittagong	75.75	62	-	-	726 GWh	8890

**Note CV: Calorific value; ER: energy recovery; C: carbon content; REP: renewable energy potential; OM: organic matter; MC: moisture content, TEp: Total electric power generation; S_A: Station service allowance; U_H: Unaccounted heat loss.

both REP and WER will help to reduce dependency on fossil fuels. The electricity generated utilizing MSW is assumed to replace coal-generated electricity in different scenarios using waste incineration plants.

4.2. Pyrolysis

Pyrolysis is a method that refers to thermal cracking that occurs without oxygen, which transforms lignocellulosic biomass (cellulose, hemicellulose, and lignin) into a solid and fluid-rich carbon [69]. This process is commonly used for collecting liquid fuel [22]. Though Pyrolysis is most commonly performed on solid biomass, it can also be used for creating bio-oil from waste [70]. After the condensation process, non-condensing low-molecular-mass gases like H_2, CO_2, CO. are produced [71]. Thermal decomposition of the organic component begins at a temperature range from 350-550 °C without oxygen and increases up to 700–800 °C. Generally, temperature, pressure, heating rate, and reactor residence time affect the products of Pyrolysis [70, 71].

The three common methods of pyrolysis are (a) Fast Pyrolysis (850–1200K) (b) Conventional Pyrolysis (550–900K) (c) Slow Pyrolysis (1050–1300K) [57]. In this process, the products from the reaction are gaseous (H_2, CO_2, CO, etc.), Char (solid residue), and pyrolysis oil. Pyrolysis can be considered as one of the best solutions to reduce environmental pollution and a cost-effective process. It is commonly used for the collection of liquid fuel [12]. Table 5 shows the factors influencing the pyrolysis of MSW for liquid fuel collection, and this type of analysis can be considered for other processes like incineration, anaerobic digestion (AD), gasification, hydrothermal carbonization (HTC). It is clear from Table 5 that the rice straw and coconut oil as a feedstock material shell show maximum moisture content of about 13.61% and 11.26 %, respectively, and hydrogen content is also higher. The quality of syngas may degrade ewith increasing moisture, and appropriate moisture content was found below 20–25% [72]. Besides with increasing moisture content, the pyrolysis temperature is also increasing, and coconut shell shows the highest value as 550 °C. Due to high pyrolysis temperature, it can be beneficial for starting a thermal decomposition. Table 5 also shows rice husk, waste paper, and tire have the maximum ash content, but plastic has the lowest. Higher ash content cause to reduction in combustion efficiency, which in turn decreases burning time. As a result, char particles are not entirely burned out of the grate. Moreover, having the most significant amount of volatile matter, vinyl has the most moderate amount of fixed carbon.

Bio-oil is not stable as conventional fuel because of its high density, high oxygenated compound, low pH [73], and mainly it is produced by flash pyrolysis [73, 74]. However, bio-oil has inadequate characteristics for internal combustion engines, like high oxygen and water levels, high viscosity, corrosivity, and instability, which prevent its widespread use. Therefore, there must need an up-gradation of bio-oil before using it in the engine. Several technologies can be used for upgrading bio-oil, such as catalytic hydrogenation,catalytic-cracking,catalytic-steam-reforming, catalytic-esterification, and emulsification [75]. Additionally, it is essential to segregate highly oxygenated organic from the water phase. Further, they need to run through a hydrotreating-hydrocracking process to upgrade and then increase their heating values and decrease corrosiveness as a potential fuel [76].

Notably, slow pyrolysis is performed at a temperature of approximately 400–500 °C on organic waste such as wood, food waste, paper, and textile waste. During the process, the heating rate under nitrogen flow is kept at 5–20 °C per min [77]. On the contrary slow pyrolysis is more simple than fast pyrolysis [77] Because the bio-oil from fast pyrolysis is an intricate combination of water and oxygenated organic compounds (organic acids, aldehydes, pyrans, alcohols, an-hydro-sugars, furans, and aromatic compounds) [78]. Nowadays, fast or flash pyrolysis is preferable at high temperatures with a short time, and in this process, biomass is speedily heated at high temperatures without oxygen [79].

The energy production time and expense can be lessened if a proper reactor can be selected. Besides, the selection of proper reactor increases the overall efficiency of the system. It is mandatory to enhance the pyrolytic bio-oil before applying it. However, there are different alternatives of enhancing the liquid pyrolytic product, such as oxidative desulphurization, fractional distillation, de-colorization. Various types of catalysts like nickel phosphide, WO3/ZrO2 are employed during these processes. Sulfur and hydrogen peroxide are eliminated or decreased during the Desulphurization process, and formic acid is usually used. The process of segregating the liquid mixture into fractions using distillation refers to Fractional distillation. However, mixing solvents or small quantitiesmixing of water to make the bio-oil into expected viscosity.

A conventional process is used for charcoal production with a slow heating rate [80, 81]. However, for fast pyrolysis, the process is executed under low temperature (850-1250k, tar) or high temperature (1050-1300k, gas). Recently, fast or flash pyrolysis is regarded as the most superior technology since the biomass materials are heated at high temperatures with short residence time without O_2 (Figure 2) [81]. As the temperature range of flash Pyrolysis is much higher than fast and conventional pyrolysis (Figure 2), it requires less time. Moreover, microwave-assisted pyrolysis is a new technology widely used for its higher volumetric heating, low residence time, top product yield, lower thermal inertia, and faster response [82].

4.3. Gasification

Gasification is a process through which the organic materials are transformed to hydrogen, carbon monoxides, and carbon dioxide with a controlled amount of oxygen or steam at high temperatures, without any combustion [45]. A shift reaction step (with steam) converts carbon monoxide into CO_2 for hydrogen production, and the produced hydrogen is further separated and purified in the gasification method [82]. Raw

Table 5. Factors influencing fuel properties during pyrolysis of MSW.

Feedstock materials	Moisture wt.%	Ash wt.%	Volatile materials wt.%	Fixed carbon wt.%	HCV (higher calorific value) (MJ/kg)	Carbon wt.%	Hydrogen Wt.%	Oxygen wt.%	N wt.%	S wt.%	Pyrolysis temperature °C	References
Rice straw	-	-	-	-	0.40	-	-	-	-	-	450	[22]
	13.61	9.54			16.35	50.93	6.04	41.61	0.83	0.23	500	[76]
Rice husk	-	-	-	-	-	39.69	5.40	-	0.67	0.21	400	[141]
	6.37	11.7	-	-	16.79	45.28	5.51	-	0.67	0.29	Below 500	[142]
Plastic	0.41	2.43	96.88	0.28	-	83.93	12.84	0.8	-	-	110	[143]
	0.46	0.02	91.75	7.77	43.0	-	-	-	-	-	-	[144]
Tyre	0.4	11.6	2.8	-	30.5	90.6	0.9	-	0.7	2.3	500	[145]
	0.37	8.27	7.78	-	30.8	88.19	0.6	-	0.1	1.9	450	[146]
Waste paper	6.49	8.86	73.12	11.53	14.345	39.5	5.29	39.67	0.11	0.08	-	[147]
Coconut shell	11.26	3.38	-	-	22.83	63.45	6.73	28.27	0.43	0.95	550	[148]

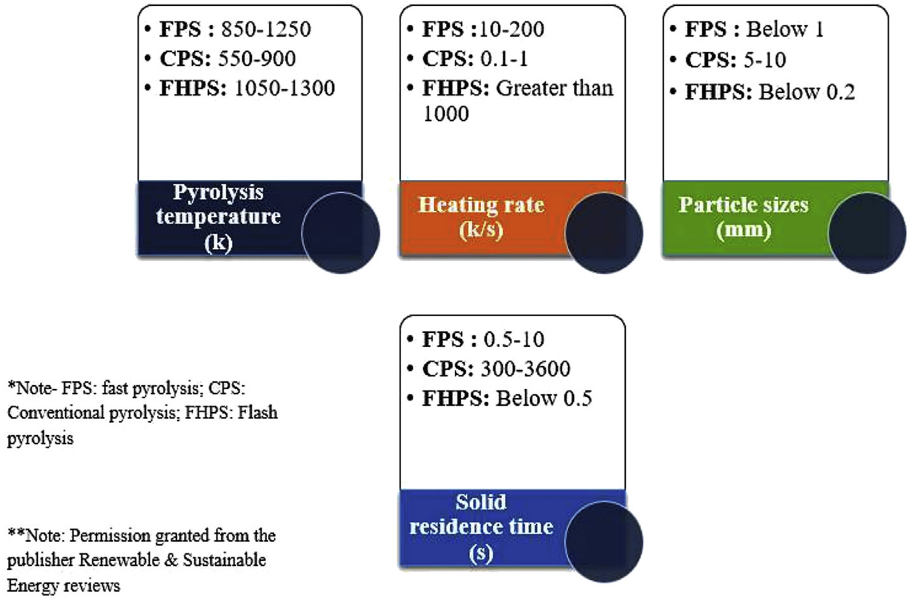

Figure 2. Main operating parameters for the pyrolysis process, adapted from [79].

materials (coal, petroleum, and organic) enter into the reactor as a dry form. In the presence of high-heated oxygen and pressure, it is exposed to a reactor or gasifier that requires energy to produce heat [57]. This process can be expected to be the best alternative for diminishing greenhouse gas consequences and has considerable potential for WtE conversion [83].

The reactor temperature is an essential operating parameter in the gasification process. The temperature profile along the reactor can determine the condition of the lower ash (i.e., the possible slag) and the amount of tar in the syngas to a certain degree. Furthermore, this reactor type and design depend on residence time. To a limited extent, the design of a fixed gasifier can vary. For an isntace, the superficial gas velocity varies in a fluidized bed and the speed of the grate elements increases in a moving grate [84].

Table 6 summarizes the description of gasification reactors and their possible characteristics. According to Table 6, the downdraft gasifier cannot be applicable for MSW because it requires low ash as fuel and exhibits lower efficiency. Nevertheless, the updraft gasifier can be applicable for power generation for its high gasification efficiency. The conversion rate of plasma gasifiers is higher than all sorts of gasifiers invented so far, approximately 100% (Table 6). Moreover, it can handle any amount of moisture present in the waste. The thermal capacity of the down-draft gasifier, updraft, bubbling FB, and circulating FB is about 1 kW- 1 MW, 1.1 MW–12 MW, 1 MW–50 MW, and 10 MW–200 MW respectively [85].However, the thermal capacity of the downdraft gasifier is lower (1 kW–1 MW). On the contrary, it is much higher for circulating gasifiers than others, which are about 10 MW–200 MW. This is because the main principle is their ability to process different types of feedstock. The advantages of a circulating gasifier are low emission process, better volume reduction capability, efficient power generating technology, generatesa circulating gasifier, low emission process, better volume reduction capability, efficient power generating technology, and fuel gas. Therefore, this can be used in a higher efficient power plant like the gas turbine. Also, it is more efficient than steam boilers, i.e., integrated with reciprocating engines.

Refuse-derived fuel (RDF) is the fuel caused by different types of waste. But the pre-process of MSW to RDF is the main disadvantage for gasification. The viability of the high-temperature purification of syngas, with a particular emphasis on the reform and desulfurization of catalytic tar, has been investigated by Chan et al. [86]. A hot syngas purification system has been designed for utilizing raw syngas produced from downdraft gasification of real MSW suitably with downward cascading of syngas temperature. The study [86]revealed that tar and sulfur compounds could beeliminated up to 90% by a hot syngas purification system

Table 6. Comparison of different solid-gas reactors for solid waste gasification [84, 87, 88].

Parameter	DFB	UFB	Bubbling Fluidized Bed	CFB	Entrained Flow	Rotary Kiln	MG	Plasma
Particle size (Fuel) (Dia. mm)	Up to 100	Up to 100	<150	<100	Fine particles <1mm	No problem at any size	<200	No problem at any size
Moisture (%)	Less than 20	Less than 50	Less than 55	Less than 55	Less than 15	No problem	Less than 60	No problem
Ash (% db)	<5	<15	<25	<25	<20	<40	<20	No problem
Ash melting point(°C)	>1250	>1000	>1000	>1000	<1250	No problem	>1200	No problem
Bulk density (kg/m^3)	>500	>400	>100	>100	>400	>100	250–350	>100
Residence time (Particles)	Until the discharge is granted	Until their discharge	Spend substantial time	For each circuit in few seconds	Very short	Very long (1–2 h)	>1 h	-
Temperature(°C)	788–1200	<500	550–1000	900–1000	1200–1500	-	-	1500–5500
Conversion	Very high conversion rates are possible	High gasification efficiency	Poor performance	High conversion is possible	-	Can be high	Over 90%	Can be high as 100%

**note: DFB: Downdraft Fixed bed; UFB: Updraft Fixed bed; CFB: Circulating Fluidized Bed; MG: Moving Grate.

combined with a downdraft fixed-bed gasifier. In this investigation, the obtained syngas from the gasifier consists of 13 ± 2 vol% CO, 2.9 ± 0.3 vol% C_2–C_5 gases, 58 ± 4 vol % N_2, 11 ± 0.4 vol% CO_2, 12 ± 2 vol% H_2, 11 ± 0.4 vol% CO_2 and the yield of syngas (dry-basis) was 2.7 ± 0.3 of RDF with N_2 and 1.1 ± 0.2 Nm^3/kg of RDF with N_2. Furthermore, the generated syngas with moisture content was 23 ± 4 vol%, whereas the particulates content was 1.9 ± 1.2 g/Nm^3. It can be said that the hot purification system shows up to 90% efficiency for the extraction of sulfur and tar and the growth in total syngas yield about 14%, and improves the cold gas efficiency around 12%. Clean syngas can be used in more effective downstream applications, such as gas engines and hybrid energy recovery systems.

Mixed plastic and rubber waste show maximum heating value, and the food waste show the minimum heating value for MSW. Moreover, the heating value of RDF decreases when more amount of glass and metal are allowed to pass through the gasifier [85]. Some RDF feed specifications for gasification are [85]: diameter 0.4–0.6in; length 2-6in; bulk density 500–700 kg/m^3; moisture 6–10%; volatile matter 71.1%; fixed carbon 114%; S 0.5%; Cl 0.4–0.6% and total no non-combustibles 11%. When the plastics are fed into other feedstock, particularly biomass and coal, the flexibility of the gasification process is significantly increased due to the synergistic impact on the reaction platform [89].

In MSW, the thermal treatment generation and environmental performance are critical for the feasibility of the process. Thermochemical and biochemical processes are less dangerous for human health and the environment. Even though the biochemical process and those of anaerobic digestion have widely accepted in the waste conversion process. Nonetheless, the gasification process still faces a significant environmental community problem [90, 91]. The gasification process is an intermediate fuel gas production process and also evident that MSW gasification can lead to fuel and chemical production and it is truly a future goal [92]. The generation of synthetic natural gas (SNG) from waste gas is a mesmerizing alternative to convert waste into valuable fuel. In traditional SNG production, the carbon conversion ratio is typically less than 50% because of the limited amount of H_2, whereas extra CO_2 has to be eliminated. The combination of the gasifier, SOEC (solid oxide electrolyzer cell), and methanation unit represented by Pan et al. [93] is proposed to provide a new SNG production system. In this system, additional H_2 for the methanation reactor is supplied by the SOEC unit that helps to improve the carbon conversion ratio (CCR) about 98% with an efficiency of 67%. Data obtained from this investigation indicated the promising application of SNG by integrating the MSW gasifier with the SOEC to achieve high-efficiency carbon recovery for waste. Moreover, the author [93] claimed that this proposed system is economically feasible. A synthesis of these data is presented in Table 7, together with the limits of the European Community and Japanese standards. This information is vital to understand the current emission characteristics of the gasification plant. As shown in Table 5, Nippon Steel, JFE, and Mitsui plants have the higher waste capacity and higher power production. However, despite the low waste capacity at Energos Averoy, power production is much higher. For the MG-AG-LT type gasifier, for the fruitful and proper combustion, it is essential to move the waste from the combustion chamber and the grate of the gasifier can do this process. Therefore, production is higher on Energos Averoy. Not only sound production, but its effect on the environment is most required. So, the capacity/production of the plant, as well as emission, should be considered. The amount of NO_x in Nippon and Ebara plants is less. NO_x has a significant consequence on the environment. For example, it reacts with oxygen and water to help cause acid rain, damages the aquatic life cycle, and is very harmful to human health. In contrast, Hg is a very harmful emission particle for the environment and public health. Because it has high toxicity and bio-accumulative properties, it may also convert to inorganic and organic forms, such as methylmercury in an organic form that is the most toxic and bio-accumulative form of mercury [94]. NO_x, SO_x, and particulate matter, i.e., the emission is low. Therefore, the Ebara TwinRec Kawaguch plant is environmentally friendly for Japan, which can be considered suitable for Bangladesh.

4.4. Anaerobic digestion (AD)

AD is a sequence of processes involving a breakdown in organic matter with microorganisms without oxygen [97]. In other words, it is a microbial method wherein various enzymes break down complicated organic matter into its pure chemicals [98]. This phenomenon happens without oxygen and leading to biogas production. While modeling AD, the operating parameters such as thermophilic or mesophilic temperature, hydraulic retention time, waste fraction degradation rate, and biogas leakage must be taken into consideration. Also, the electricity and heating efficiency are essential parameters generated throughout the biogas combustion [99].

Four significant processes are included in anaerobic digestions. They are (a) hydrolysis, (b) acidogenesis, (c) acetogenesis, and (d) methanogenesis. A relatively long digestive time (typically 20–40 days) leading to a long duration of microbial response can be a critical problem in applying anaerobic digestion. Also, the hydrolysis rates for complex organic substrates have been observed by the most researchers [100, 101, 102]. It is reported [103] that unwanted volatile fatty acids or toxic by-products are formed during the hydrolysis step.

Another problem that can happen by feedstock. A suboptimal C/N ratio of the single feedstock may exist, resulting in unstable digestion. Additionally, excessive levels of protein can lead to a lower C/N ratio in the feedstock. Protein compounds can produce ammonia, and this ammonia, if it is built enormously in the digester, may play a significant

Table 7. Some certified emissions from waste gasification plants. Adapted from: [84, 92, 95, 96].

The company, plant location	Nippon steel Kazusa, Japan	JFE/Thermoselect Nagasaki, Japan	Ebara TwinRec Kawaguchi, Japan	Mitsui R21 Toyohashi, Japan	Energos Averoy, Norway	PlascoEn. Ottawa, Canada	EC Standard, Japanese
Gasifier type	DD-EAG-HT	DD-OG-HT	ICFB-AG-(LT + HT)	RK-AG-LT	MG-AG-LT	PG-HT	standard
Waste capacity	200 tonnes/day	300 tonnes/day	420 tonnes/day	400 tonnes/day	100 tonnes/day	110 tonnes/day	
	MSW	MSW	MSW	MSW	MSW	MSW	
Power production (MWe)	2.3	8	5.5	8.7	10.2	-	-
Emissions, mg/m^3_N (at 11% O_2)							
Particulate	10.1	<3.4	<1	<0.71	0.24	9.1	10/11
HCL	<8.9	8.3	<2	39.9	3.61	2.2	10/90
NO_x	22.3	-	29	59.1	42	107	200/229
Hg	<0.05	<0.05	<0.005	-	0.0026	0.0001	0.03/-
Dioxins/furans n-TEQ/m^3_N	0.032	0.018	0.000051	0.0032	0.0008	0.006	0.1/0.1

DD- Down draft, EAG- Oxygen enriched-air gasifiers, HT- High-temperature gasifiers, OG- Oxygen gasifiers, ICFB- internally circulating fluidized bed, LT- Low-temperature gasifiers, RK- Rotary kiln gasifiers, MG- Moving grate gasifiers, PG- Plasma gasifiers.

role in accelerating the generation of volatile fatty acids and digestive system failure [103]. Even so, feedstocks which are containing a high level of carbohydrate generate more CO_2 [104].

In Bangladesh, a good portion of livestock residues is being left in the agricultural land. These can be used for biogas production utilizing anaerobic digestion (AD), which is prevalent in rural areas of Bangladesh. Also, biogas can be made from cow dung or cow dung mixture with chicken excreta. Around 0.29 million tonnes of residue per day can be converted into biogas [105, 106]. Nowadays, the use of renewable energy is increasing day by day instead of using other conventional energy sources to prevent GHG emissions, save natural resources, and increase energy efficiency. However, biogas production from organic solid waste (OSW) is becoming more popular countrywide. This is because of having economic durability, environmental attractiveness, and some important characteristics [105, 107]. In Bangladesh, 3 billion m^3 biogas can be produced from 24 million cattle and 75 million poultry. Already 19,596 biogas plants have been installed, and the production rate of gas is 26.12 m^3/BGP per day [22, 108]. Table 8 presents the relationship between influencing factors such as feedstock material, biogas yield, pH, retention time (RT) in biogas production. As can be seen, the yield level has risen with increasing ratio, and the yield of BW: DMS (BW- body weight) is much higher than other material ratios (569 ml/kg). The ratio of VFW: CD, VFW: CD, KW: CM, BW: SS is 1: 1, 1: 1.2, 4: 1, 1: 26.6 are increased while yield are increased in 1.20, 2.0, 13.21, 94, respectively. Mamun et al. [109] investigated the dominance of feedstock ratio on biogas yield for optimal biogas production. The author found the highest biogas yield of 591.3, 432.9, and 450.6 L/kg for CW: CM (50:50), VW: CM (25:75), and FW: CM (25:75), respectively. The result indicates that biogas yield increases with an increasing feedstock ratio. The analysis of Table 8 shows that the pH levels for yield 1.20, 94, and 569 are 6.8, 7.2, and 8.1, respectively. Thus, as the pH increases, the amount of biogas yield increases. Jayaraj et al. [110] has investigated the dominance of pH biogas produced from food waste through the AD process. This experimental result shows that PH-7 has the highest biogas yield and 1.24% higher than PH-5. Again, with the biogas yield, the temperature effect exists. An experimental result showed that the total production of biogas decreases significantly with the drop in temperatures [111].

Furthermore, Table 8 shows the efficiency of biogas production and the influencing factors of AD. The total biogas energy potential is approximately (66.7×10^6) kWh from animal manure and residues feedstock, in which cattle feedstock, poultry feedstock, rice-straw bedding consists of roughly 70%, 16%, 14%, respectively [96]. Residues of the olive oil industry, in particular, are a superb food for the AD plants since these waste are produced in large amounts in the short term and cannot be biodegraded as organic and phenolic compounds concentrate at high concentrations [112]. For, large-scale digester, the cattle dung might be very useful in the semi-continuous model of AD [97], which is also supported by the information provided in Table 8.

Table 8. The efficiency of biogas production and the influencing factors of AD [22, 107, 113, 114, 115].

Feedstock materials	Ratio	Temperature (°C)	RT	pH	Maximum biogas yield (ml/kg) (ml: biogas; kg: dry based, decomposed based)
VFW:CD	1:1	25	15	6.8	1.20
VFW:CD	1:1.2	25	7	-	2.0
FW	-	25	10	-	0.15
BW: DMS	1:8.8	38	15	8.1	569
BW: SS	1:26.6	38	16	7.2	94
KW:CM	4:1	35	10–13	-	13.21

** Note: CD = Cow dung; RT = Retention time; FW = Fish waste; Sr= SS = Sewage sludge; DMS = Digested maize silage; VFW = Volume of fish waste; WP = Waste paper; KW = Kitchen waste; CM = Cow manure. BW- body weight.

4.5. Hydrothermal carbonization (HTC)

Hydrothermal carbonization (HTC) is a sequence of steps through which energy-dense, homogenized, and carbon-rich solid fuels are made, also known as hydro-char. Because of the potentiality of converting wet organic feedstock into energy; this thermochemical conversion approach can draw a great interest. During the process, the biomass is blended with the water and is heated in an enclosed system at a temperature ranges from 180-260 °C with the reaction times from 5 min to 4 h under the pressure of 2–6 MPa. Generally, during the process, it does not control the pressure of the reaction and is autogenic with the saturation vapor pressure of water (subcritical-water) corresponding to the reaction temperature.

For heat and power production, the produced solid hydro-char that is almost similar to coal material can be utilized as a solid fuel. The HTC process has been applied to lignocellulosic biomass, sewage sludge, algae, food waste, and municipal solid waste [116, 117]. The process of coal formation can be compared with this process from biomass energy. It can be regarded as one of the most favorable treatment since it can manage a lot of water content and decarboxylation, dehydration, and polymerization processes that are mainly involved in this process [116]. The final product can be more energy-dense by separating carboxyl and OH groups due to reducing the O/C ratio.

Figure 3 explains the effect of different fundamental process parameters on HTC. Various literature experimented with taking different temperatures [118, 119, 120, 121]. However, in most cases, the optimum temperature lies between 200-250 °C (Figure 3). Residence time is another essential factor that has a reciprocal relation to temperature. Nevertheless, it is not possible to decide on the pH of feed water as the number of literatures on this is rare. The heating rate usually lies between 2-140 °C/min. A higher heating rate cannot favor hydro-char formation, preferably with the increase of heating rate. Zhang et al. [122] investigated the effects on the hydrothermal process of grasslands perennial heating rates (5–140 °C min^{-1}). That indicates that hydrocarbon yield declined declines when the heating rate increases from 22-23% to 8–9%. In another research, Zhang et al. [123] demonstrated that the hydrocarbon yield decreased by about 19-9%, while the heating rate went up from 5 °C to 140 °C/min (feedstock: corn stover and wood chips). With a high heating rate, drawbacks to the heat transfer can be lessened [124]. Therefore, the hydrothermal liquidation process usually requires a high heating rate. A survey by Brand [125] revealed a similar tendency and the result showed that the increase of 2º-20 °C min^{-1} heating rates is advantageous for biomass transformation to bio-oil. Moreover, the H/C and O/C ratios decreased with an enhancement in temperature and residence duration at low heating rates. Consequently, a low heating rate may help to improve the level of hydro-char carbonization. This suggests that hydro-char and liquid products can be distributed at suitable heating rates during HTC [126]. Besides, the plant efficiency depends on the HCV of hydro-char. Generally, plant efficiency represents the percentage of the total energy content of a fuel converted into electricity. So, the HTC plant efficiency is provided by the ratio of thermal energy contained in the hydro-char produced and the total energy used to produce it given by the following equation [165].

$$\text{HTC Plant efficiency} = \frac{\text{Energy}_{\text{hydrochar, HCV}}}{\text{Energy}_{\text{biomass, HCV}} + \text{Energy}_{\text{electrical}} + \text{Energy}_{\text{thermal}}} \tag{1}$$

The yield of hydro-char reduces with the increase of temperature, and the low-temperature HTC process generates HC of lower calorific value and carbon content. However, the amount of moisture content can be reduced significantly by increasing the time duration that increases the HC yield. For instance, the degradation of cellulose is like the pyrolysis process when the temperature is 200 °C; but, as the temperature goes up (230–240 °C) the atomic ratio of O/C and H/C decreases due to hydrocarbon condensation [118].

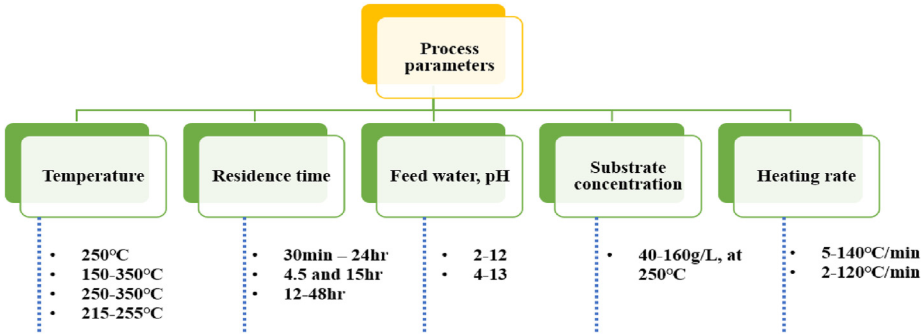

Figure 3. Process parameters related to HTC including different values, adapted from: [118, 119, 120, 121, 122, 125, 127, 128, 129, 130, 131].

The nuclear rate decreases firmly with temperature when using lignocellulosic material such as dry palm fruits bunched at 150 °C, 250 °C, and 350 °C [119]. However, the reliable product of cellulose decreases due to the increase in temperature above 200 °C. Another research showed that the H_2 concentration increases (10.6%) when the heat increases from 250 °C to 350 °C and CH_4 percentages from 1.92% to 4.89% [120]. Further, another experiment suggested that the mass yield of hydro-char decreases (69.1–50.1%) due to the increase of temperature (215–255 °C) [121]. In hydro-char formation, residence time plays a vital role because long residence time may increase reaction time. However, increasing residence time (30min-24 h at 240 °C) causes cracking off the hydro-char surface, which is found while converting hydro-char from water hyacinth [127]. Furthermore, the pH of organic acid production decreases during the HTC process [132, 133]. An experiment showed that at a pH of 12.5-hydroxymethyl-furfural-a- aldehyde (HMF) had shown its minimum content, but that phenomena were not found during the fast degradation process [130]. Another result showed that hydro-char and liquid product quality both varied with the pH [130]. It is also found that the stable yield drastically reduced at high pH of 13, while there was no mark-able change observed for a range of pH 4–10 [126,131].

5. Selection of proper method

Bangladesh has excellent energy potential from MSW. The total potential for renewable electrical generation by MSW in Bangladesh is observed to be the range 4.2×10^3–5.6×10^3 GWh by 2030, and 6.6×10^3 -11.6×10^3 GWh by 2050 [54]. The five processes mentioned above would be sufficient for energy production from MSW. However, some parameters such as moisture content, calorific value, residence time, etc. should be chosen to select the suitable method. The cost, including machineries, installation, land, and operational cost, is the most important concern for adopting the methods. Finally, the payback period, merits, and demerits of the corresponding method should also be considered when choosing the suitable one. Table 10 mainly summarizes the energy parameters of different process plants and their conversion efficiency with advantages. From below Table 10, it can be seen that the energy conversion efficiency of incineration, HTC is about 20–48% higher than other processes. Despite reducing waste volume by 80%, the incineration process is not environmentally and economically feasible compare to other processes due to its high operation cost and harmful pollutant production. The emission can be controlled by using exhaust gas treatment technology and fly ash stabilization technology in the incineration process. If the profit margin between the substituted fuel and waste oil is high enough and the burning furnace is sufficiently large, flue gas treatment investments can be financially beneficial.

Furthermore, HTC plant efficiency is 78%, and an attractive treatment for bio-waste, still waste disposal, and the pre-drying process is expensive but environmentally feasible. However, although gasification, AD, and pyrolysis process efficiency are low, these are worth discussing. As Bangladesh is a developing country, efficiency and environmental effects must be given more prominence. From this point of view, HTC can be considered as a suitable process for Bangladesh. In addition, the Incineration process is also more cost-effective than other methods, which are clear from Table 9, though for incineration, the operational cost is comparatively high.

On the contrary, the payback period of the AD and pyrolysis process is 4.9–7.8 years and 6.5–7.5 years, respectively whereas incineration needs 8–12 years and for HTC it requires almost 10 years. However, it is necessary to mention that capital costs and payback periods are presented based on machine and land costs and don't cover the applied treatment process. Though literatures are rarely found for the HTC method, the suitability is much higher for both processes in terms of their cost-effectiveness and efficiencies. Moreover, from an ecological point of view, HTC has the highest preference because of its lesser generation of pollutants and toxic gas during processing [134]. Though all the adopted methods are environmentally friendly, incineration, AD, and gasification tend to generate harmful gases, high concentrations of pollutants, and other odor pollution, which is clear from Table 9.

Moreover, contains carbon in HTC process below 61.5 wt.% are due to lower process conditions. The average value can be taken as an indication of the successful dehydration of biomass. This information and based on the waste resources mentioned above, the HTC method can have the highest preference for adopting and harnessing energy from solid waste in Bangladesh. Again, it is worth mentioning that though these two methods are not well established in Bangladesh, government and other initiates should come forward for improving more research on it and raising awareness to adopt these techniques.

6. Circular bioeconomy economy (CBE) in Bangladesh

The bioeconomy includes products derived from renewable biomass, such as plants, and organic waste streams such as food waste. The bioeconomy, of course, is not just products-it is also made up of people and businesses [135]. The circular bioeconomy combines two key sustainability concepts. Firstly, it involves using more renewable resources for energy, chemicals, and materials – such as plant-based products. Second, it works to keep these sustainable materials and products in use longer than to throw them away [135].

Circular Bioeconomy is defined as the intersection of the bioeconomy and the circular economy based on products, share, reuse, cascading use, resource-efficient value chain, nutrient cycling, and organic recycling, etc. In Bangladesh potential for bioeconomy-derived waste remains uninvestigated and there are different outstanding chances in waste management to transform it into a robust business platform. Sustainable use of waste in a great extent as renewable feedstock in circular-biorefinery format influences the economy and enhances conversion from fossil-based to bio-based this application has a great significant and efficacious dominance on the environment [136]. Because of the scarcity of proper separation of waste, which is the significant factor, Bangladesh's waste management services market is losing its waste recycling potential. A solution to using these renewable sources without causing

Table 9. Comparison of five discussed methodology.

Suggested methodology	Capital cost (USD)	Production (USD)	Payback period (Years)	Primary products	Disadvantages
Pyrolysis	66×10^6 (0.1×10^6 kg/h, plant capacity) [149]	1.031/kg [149]	7 [150]; 7.5 [151]; 6.5 [152]	Char, bio-oil, and syngas [57, 153, 154]	High cost, The high viscosity of pyrolysis [57, 155, 156]
Incineration	3.6×10^6 (5.44×10^3 kg/h) [157]	0.87/kg [158]	12.73 [159]; 8-12 [160]	Heat [57]	High operation cost, Produce harmful pollutants, [57, 161]; Odor pollution [162]
Gasification	0.14×10^6 [163]	15/kg [163]	9.73 [164]; 11 [165]	Syngas producer gas [57]	Inflexible, High risk of failure [57]; Compatibility issue between the engines and syngas, high concentration of pollutants [166]
AD	0.37×10^6 [167]	73.81/MWh [167]	4.94 [164]; 7.8 [167]	Biogas and digestate [57]	Unsuitable for wastes containing less organic matter [57]; Organics degradation kinetics is quite slow [168]; non-desirable volatile fatty acids (VFA) formed during hydrolysis step [169]
HTC	1.3×10^6 [170]	0.18/kg [171]	10 [172,173]	-	Expensive waste disposal and pre-drying process [174]

damage to the environment is the valorization of waste through advanced technologies and biological processes that provide a unique advantage in resolving the current environmental challenges [136]. There is a large proportion of metals and minerals not stored in the economy but lost in the environment or land and Often, fossil or bio-based products are landfilled or the environment and are lost to the circular economy [137].

Bio-based manufacturing fits the concept of using residues and waste materials as feedstocks for biorefining. The waste hierarchy controls cascading use – though not before – if a biomass-based product is created. The cascading principle thus closes the gap between the use of biomass and the hierarchy of waste. In Bangladesh, two methods may support CBE in the future that discussed below:

6.1. Incineration

Waste markets can be disrupted as some waste materials currently being recycled, landfilled, or incinerated for biorefineries could be constrained in the future and bio-waste is diverted from incineration, which is complicated by the high moisture content of bio-waste [138].

One of the major problems in Bangladesh is the energy crisis; the other is not utilizing household waste properly. So, the energy supply crisis and environmental pollution are a threat to the CBE. The right solution will be to take energy from the waste and apply it to the bio-economy. As shown in Table 10, incineration can reduce the volume of waste by 80% and heat production by 70–80%. Also, it is much lower than other carbon emission processes, and it requires a minimum footprint compared to other disposal alternatives. For these reasons, incineration helps to increase the lifespan of landfills. Thus, it will contribute significantly in the economy of Bangladesh in eliminating the energy crisis, reducing dependence on fossil fuels, and protecting the environment from pollution.

6.2. AD

In the circular economy, biodegradable plastics can add value. They can be processed in industrial composting installations or contribute to biogas production in anaerobic digestion plants. The bread collected can be turned into fertilizer, but plants are being made to create a large anaerobic digestion plant to produce biogas from waste bread. The combination of the most conventional (e.g. anaerobic digestion and composting) and the most modern (cellulose biorefining) is waste bio-processing waste [138]. The flexibility of the digestive system and its digestive capacity in a wide range of organic food products ensures the role of anaerobic digestion and biogas in circular economies while producing a significant range of products [139].

The AD process is used to decompose MSW and aids in biogas conversation. This biogas is a sustainable power source containing methane, carbon dioxide, and trace gases. It is used as fuel in ignition motors, which produce both power and heat. It is possible to capture methane through the AD process for use as an essential inexhaustible fuel. Again, greenhouse gas discharge helps reduce in two ways [140]: Through forestalling uncontrolled methane outflows and by producing energy, which ejects the utilization of nonrenewable energy sources. Also, the nutrient-rich by-product can be used as fertilizer in the agricultural sector in Bangladesh.

Table 10. Process selection with efficiency and advantages.

WTE process	Required parameters for energy conversion efficiency	Energy conversion efficiency (%)	Process benefits or advantages
Pyrolysis	Thermochemical reactor efficiency	60–71.60	• Produce high quality fuel • Reduce MSW volume 50–90%
Incineration	Heat production efficiency	70–80	• Reduce MSW volume up to 80%
Gasification	Electrical efficiency	31	• Production of fuel oil/gas that can be used for various purpose
AD	Electrical efficiency	36	• Preferred for biomass gas with high water content • Lower composition of CO_2
HTC	Plant efficiency	78	• Attractive treatment option for bio waste and environmentally friendly

**Note: Efficiencies adapted from: [175, 176, 177]; Advantages adapted from: [57, 134, 159].

It is expected that in 2025, the progress of the Circular bioeconomy sector of Bangladesh will increase. The public and private sectors will benefit, and the government and other NGOs will have to come forward to develop a sustainable business model. Solid waste and municipalities are the main stakeholders; they are essential in revenue generation. The business model of Bangladesh can be arranged in three ways: (a) public service activities will have to be increased where the waste will be collected from households, (b) processing activities will have to be better where the waste will be transformed, (c) there will be marketing activities that will have the opportunity to recycle waste and re-enter the economy. Furthermore, Government support, such as soft loans or land allocations, will positively impact the sector. In the waste management sector, start-up companies have an everlasting scope and possibility, and well-conceived business models will advantageously maintain their position in a dynamic market environment. In addition, the waste biorefinery field has considerable scope for innovation and requires liberal financial support to strengthen its applications.

However, waste-derived circular bioeconomy has remarkable opportunity and prospective for industrial innovation if tactical knowledge is scrutinized through the integration of suitable science and technology with beneficent financial aid. Adopting bioeconomy-derived waste can address most of the Sustainable Development Goals more precisely. A circular bioeconomy reduces waste and pollution, such as plastics in the ocean, and uses fewer finite resources. It's much better for Bangladesh. A circular bioeconomy also encourages rural communities to build on biomass by providing new business opportunities and investments in Bangladesh in the future.

7. Conclusions

This paper focuses on renewable energy (electricity, biofuel, and char production) potential in major cities of Bangladesh through MSW generation with five methodologies. Nevertheless, the most important findings are discussed below:

1. It would be practical to establish a small-scale plant for converting waste into energy in Bangladesh as Bangladesh has not effectively adopted any method for waste to energy generation so far (except pyrolysis). Also, the geographic area of each city and number of produced wastes are not adequate enough to establish large scale plants.
2. Large plants will not be cost-effective because of the lack of waste carrying facilities. Moreover, the investment amount for the development of the collection system should be sufficiently covered by improving the income of large-scale facilities. Depending on the size of the city, the size of the facility can be changed from large to medium and small.
3. Pyrolysis is used widely in this country, and nowadays, microwave-assisted pyrolysis is taking place for its low residence time and high volumetric efficiency as discussed earlier.
4. Analysis suggest that HTC may take the most elevated position in Bangladesh in the future for its higher efficiency and better environmental benefits. However, it is challenging to evaluate the potentiality of those methodologies for producing energy due to insufficient research.

In Bangladesh, economic instruments may be feasible for MSW management in terms of cost-effectiveness. Additionally, administrative solid structure is needed to manage the generation of MSW. Seminars and rallies should be arranged to increase public awareness. Effective MSW management calls for the active participation of local governments, communities, and NGOs.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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